Textural properties of vegetables: a key parameter on ultrasonic assisted convective drying

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ABSTRACT

The application of power ultrasound could constitute a way to improve traditional convective drying systems. There still exists a lack of knowledge on this technology in order to address industrial applications. The aim of this work was to identify the influence of the textural properties of different vegetable products on the ultrasonic assisted convective drying. For that purpose, experimental drying kinetics (40 °C and 1 m/s) of different vegetable products (orange and lemon peel, carrot, potato and eggplant) were carried out applying different ultrasonic powers (0, 6, 12, 18, 25, 30 and 37 kW/m³). In every product, a similar diffusion model was used to identify an average effective diffusivity for the different ultrasonic powers. Product’s textural properties were assessed by Textural Profile Analysis (TPA).

Linear relationships were established between the identified effective diffusivity and the applied ultrasonic power for the different products. The positive slopes of the linear relationships determine the ultrasonic effectiveness over the mass transfer. The slopes were well correlated (R²=0.924) with the hardness for every product, the harder the product, the lower the slope. According to these results, the efficiency of the ultrasonic application on the drying process depends on the structure of the material being treated. Therefore, a preliminary instrumental textural analysis could be used to evaluate the potential of the ultrasonic application for the drying of a specific product.

Keywords: Dehydration; Mass transfer; Ultrasound; Texture profile analysis.

INTRODUCTION

The increasing need for producing high quality dry products has led to combine traditional drying methods with non-conventional energy sources. In this sense, ultrasonic energy is very promising because it can act without affecting the main characteristics and quality of products due to its low heating effects [1]. The improvement of water transfer rate from the solid surface to the air medium is provoked by the effects on the solid-gas interfaces: pressure variations, oscillating velocities and microstreaming. Moreover, the “sponge effect” may improve the internal water transfer due to compression and expansions cycles produced by the ultrasonic waves in the material [2]. The intensity of ultrasonic effects has been shown to depend on the operational variables, such as, air velocity [2], temperature [1] and applied ultrasonic power [3]. Product characteristics also influence the absorption of ultrasound; so far only porosity has been addressed. García-Pérez et al. [3] already reported that high-porosity products are more prone to the “effect sponge” due to its weak structure, which involves a low structural resistance to the mechanical stress. Therefore, it should be expected that the ultrasonic effects on the material being dried will be linked to product’s textural properties.

Textural properties of vegetable tissue are related with histological factors, such as, size, shape, adhesion, intercellular spaces, wall properties and turgor pressure of the cells [4]. Changes in the composition and structure of the cell wall, as well as in the tissue structure, prompt a variation in plant texture. During processing of fruits and vegetables, the cell walls undergo a series of changes in the macrostructure, microstructure and composition, as well as in material and functional properties [5]. For evaluating textural properties on vegetables is essential to understand their mechanical behavior in terms of different rheological parameters. In this sense, texture profile analysis (TPA), which is related with compression and deformation tests, is a method commonly used to evaluate mechanical properties on this kind of products. TPA analysis is related with the sample size and shape, ratio of compression probe size versus sample, degree of compression, deformation rate, number of bites and replicates per mean value [6].

The aim of this work was to identify the influence of the textural properties of different vegetable products on the ultrasonic assisted convective drying effectiveness.
**MATERIALS & METHODS**

**Drying experiments**

Experimental drying kinetics of different vegetable products already reported in previous works were used: carrots and potato cubes (8.7 mm) [3], eggplant cylinders (height 20 mm and diameter 24 mm) [7], orange and lemon peel slabs (thickness 5.95 ± 0.41 mm) [3,8]. In every case, drying experiments were conducted at 40 ºC and 1 m/s applying different ultrasonic powers (UP): 0, 6, 12, 18, 25, 30 and 37 kW/m³ until samples lost 70 % of their initial weight. The ultrasonic power is defined as the electric power supplied to the ultrasonic transducer divided by the volume of the drying chamber, thus, it really refers to a power density.

**Modeling drying kinetics**

Drying kinetics were modeled according to the diffusion theory. The differential equation of diffusion can be obtained combining Fick’s law and the microscopic mass balance. For infinite slab, cube and finite cylinder geometry the diffusion equation are shown in Eqs. 1, 2 and 3 respectively, considering a constant effective moisture diffusivity and isotropic solid. [9]

\[
\frac{\partial W_p(x,t)}{\partial t} = D_e \left( \frac{\partial^2 W_p(x,t)}{\partial x^2} \right) \quad \text{Eq. 1}
\]

\[
\frac{\partial W_p(x,y,z,t)}{\partial t} = D_e \left( \frac{\partial^2 W_p(x,y,z,t)}{\partial x^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial y^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial z^2} \right) \quad \text{Eq. 2}
\]

\[
\frac{\partial W_p(x,r,t)}{\partial t} = D_e \left( \frac{\partial^2 W_p(x,r,t)}{\partial x^2} + \frac{\partial^2 W_p(x,r,t)}{\partial r^2} + \frac{1}{r} \frac{\partial W_p(x,r,t)}{\partial r} \right) \quad \text{Eq. 3}
\]

Where \( W_p \) is the local moisture (kg w/kg d.m.), \( t \) is the time (s), \( D_e \) is the effective moisture diffusivity (m²/s) and \( x, y, z \) and \( r \) represent the characteristic coordinate in slab, cube and cylinder geometry (m).

Diffusion equations were solved by assuming the solid symmetry, uniform initial moisture content and temperature and a constant product shape during the drying process. The external resistance to mass transfer was neglected, thus, mass transfer was assumed to be entirely controlled by diffusion mechanisms. The analytical solutions [9] of the governing equation for different geometries (infinite slab, cube and finite cylinder) in terms of the dimensionless moisture content are given in Eqs. 4, 5 and 6, respectively.

\[
\psi(t) = \frac{W(t) - W_e}{W_0 - W_e} = \sum_{n=1}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \left( \frac{D_e(2n+1)^2 \pi^2}{4L^2} \right) \quad \text{Eq. 4}
\]

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\]

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\]

Where \( \psi \) dimensionless moisture, \( W \) the average moisture content (kg w/kg d.m.), \( W_0 \) the critical (initial) moisture content (kg w/kg d.m.), \( W_e \) the equilibrium moisture content (kg w/kg d.m.), \( \alpha_n \) the eigenvalues and \( L \) the half-length (m) and \( R \) the radius (m).

The effective moisture diffusivity was identified by using an optimization procedure that minimized the sum of the squared differences between experimental and calculated average moisture content of samples. For that
purpose, the non-linear optimization algorithm of the Generalized Reduced Gradient (GRG), available in Microsoft Excel™ spreadsheet from MS Office 2007, was used. The goodness of the fit was determined by calculating the percentage of explained variance (%VAR, Eq. 7) [10].

\[
\%\text{VAR} = \left[ 1 - \frac{S_{xy}^2}{S_y^2} \right] \cdot 100 \quad \text{Eq. 7}
\]

Where \( S_{xy}^2 \) and \( S_y^2 \) are the standard deviation of the estimation and the sample, respectively.

The multifactor ANOVA and the LSD (Least Significant Difference) intervals were chosen to evaluate the significance (p<0.05) of the differences between the effective diffusivity values identified. The statistical analysis was carried out using the Statgraphics Plus 5.1 software package.

Texture

Textural properties of the different products were measured with a TA-XT2 texturometer (SMS, Godalming, UK) with a load cell of 25 kg. Texture profile analysis (TPA) was carried out by two compression cycles between parallel plates performed on cylindrical samples (diameter 7.70 mm, height 6 mm) in the fresh products, at 25 % strain, using a flat 75 mm diameter aluminum plunger (SMS P/75) and with a 5 s set period of time between cycles. In the case of orange and lemon peel, the TPA analysis was carried out in both faces of the albedo and flavedo tissue and averaged. Hardness, adhesiveness, cohesiveness, springiness, chewiness and resilience were calculated from force/deformation profiles [4]. At least, 10 measurements were performed for each set of samples.

RESULTS & DISCUSSION

Modeling drying kinetics

The average effective moisture diffusivity (\(D_e\)) identified for the different products are shown in Figure 1. In the experiments without ultrasonic application (0 kW/m³) the identified effective moisture diffusivities are similar to other already reported for these products [11, 12].

![Figure 1](image.png)

**Figure 1.** Influence of the ultrasonic power (UP) on the effective moisture diffusivity. Average values ± LSD intervals (p<0.05) are plotted.

As observed in Figure 1, the applied ultrasonic power during drying showed a significant (p<0.05) influence on the effective moisture diffusivities. The ultrasonic effects were dependent on the applied power, the higher
the power, the greater the identified effective diffusivity. For the different products tested, linear relationships between the ultrasonic power level and the effective moisture diffusivity were found in the power range tested in this work (0-37 kW/m³) (Figure 1). The slope of the linear relationship may be used to estimate the effectiveness of the ultrasonic application. The improvement of the Dₑ values may be associated with the mechanical effects brought about by applying ultrasound to the material being dried. The alternating cycles of expansions and contractions (“sponge effect”) may contribute to easy water leaving the solid matrix, thus reducing the internal resistance to mass transfer [1]. Thereby, the larger the improvement (slope) by the ultrasonic application, the higher the intensity of the mechanical effects in the material.

The proposed diffusion model provided low percentages of explained variance (< 90 %). However, similar trends were observed between experimental and calculated data. In order to obtain a better fit of experimental data, the hypothesis assumed to solve the diffusion equations should be reconsidered.

**Texture**

The texture parameters calculated from the TPA curves are shown in Table 1.

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>HARDNESS (N)</th>
<th>COHESIVENESS (-)</th>
<th>SPRINGINESS (-)</th>
<th>CHEWININESS (N)</th>
<th>ADHESIVENESS (Ns)</th>
<th>RESILIENCE (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARROT</td>
<td>44.4±1.8</td>
<td>0.56±0.02</td>
<td>0.99±0.07</td>
<td>24.7±1.5</td>
<td>-0.03±0.01</td>
<td>0.36±0.01</td>
</tr>
<tr>
<td>POTATO</td>
<td>31.2±1.1</td>
<td>0.40±0.02</td>
<td>0.99±0.09</td>
<td>12.5±0.9</td>
<td>-0.11±0.01</td>
<td>0.28±0.01</td>
</tr>
<tr>
<td>LEMON PEEL</td>
<td>15.1±3.1</td>
<td>0.60±0.03</td>
<td>0.99±0.09</td>
<td>9.0±2.1</td>
<td>-0.01±0.01</td>
<td>0.38±0.02</td>
</tr>
<tr>
<td>EGGPLANT</td>
<td>9.9±4.4</td>
<td>0.48±0.05</td>
<td>0.98±0.06</td>
<td>4.7±2.5</td>
<td>-0.05±0.02</td>
<td>0.32±0.02</td>
</tr>
<tr>
<td>ORANGE PEEL</td>
<td>9.8±2.6</td>
<td>0.56±0.06</td>
<td>0.96±0.20</td>
<td>5.2±2.1</td>
<td>-0.01±0.02</td>
<td>0.31±0.04</td>
</tr>
</tbody>
</table>

As can be observed in Table 1, the main differences for the products tested in terms of texture were observed in hardness and chewiness values. On the one hand, carrot and potato showed the higher values of hardness and chewiness. According to microstructural observations carried out by other authors, carrot is mainly constituted by two types of tissues: the phloem and the xylem. The phloem shows a strong structure because it is composed of well-joined cells along their cell walls. Besides, xylem presents vessel elements, which have very thick and lignified walls. The structure of phloem and xylem is the responsible of the largest values of hardness and chewiness in carrot [13]. The potato tissue has also a system very close of small and spherical cells. The cells are randomly positioned and contain numerous round and oval starch grains of crystalline structure. Because of the relatively high volume of cell wall material and strong cohesion in carrot and potato material, the values of hardness and chewiness were higher than eggplant, lemon and orange peel [14].

On the other hand, eggplant and orange and lemon peels showed the lowest values of hardness and chewiness. García-Pérez et al. [15]observed by Cryo-SEM that the eggplant is composed by two main tissues, an external layer named epicarp and the endocarp, which practically occupies the whole flesh fruit. In this sense, endocarp is characterized by tubular and interconnected cells and it is the responsible of the highly unconsolidated porous structure of the eggplant. In the case of citrus peels, the two characteristic tissues are flavedo and albedo. The flavedo constitutes the external layer and may be considered a compact structure with spherical or oval cells and without intercellular spaces. However, the albedo is characterized by long tubular cells and large intercellular spaces, conferring to the peel a weak structure [8]. The higher value of hardness and chewiness for lemon in comparison to orange peel may be attributed to a thicker flavedo tissue. Both, citrus peels and eggplant may be considered non-compact structures with a low mechanical resistance to deformation.
As can be observed in Figure 2, a linear relationship between the slopes of the linear relationships of the effective diffusivity and the acoustic power (Figure 1) versus hardness was found, the higher the hardness of the tested products, the lower the slope. That means that the improvement due to ultrasound effects on the effective diffusivity is well correlated (at 99% confidence level) with the hardness of the product. This fact confirms that the mechanical compressions and expansions (“sponge effect”) produced in the materials by ultrasound were more intense in soft products resulting in a more effective water removal. Furthermore, the acoustic effects on boundary layer of intercellular spaces could be also more intense in this type of products due to a larger porous net [3]. In the case of the chewiness parameter, a similar behavior was observed than that found for the hardness. However, other texture parameters calculated (cohesiveness, springiness, adhesiveness and resilience) were not well correlated with the effect of ultrasound.

CONCLUSIONS

According to the results of this work, the ultrasonic effectiveness on the drying process depends on the structure of the material being treated. A preliminary instrumental textural analysis could be used to evaluate the potential of the ultrasonic application for the drying of a particular product.

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